Spectral reflectance of whitecaps

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[1] Spectral properties of whitecaps are of importance for color ocean remote sensing and aerosol optical thickness probing from satellite-based instruments. They also influence planetary albedo and climate. In particular, whitecaps may affect the response of the climate system to changes in greenhouse gases and other atmospheric constituents. Several experimental measurements of whitecap spectral reflectance have been performed both in the surf zone and in the open ocean, which indicate that oceanic foam cannot be considered as a gray body (e.g., for satellite remote sensing techniques). This paper is devoted to the interpretation of experiments performed in terms of the radiative transfer theory. Only the case of a semi-infinite foam is studied in detail. However, results can be easily extended to the case of finite foamed media having large optical thickness. The model introduced is capable of explaining main features observed, like a sharp decrease of the foam spectral reflectance in the infrared as compared with the visible part of the electromagnetic spectrum and a high correlation of the foam reflectance R and the water absorption coefficient α. A simple method to retrieve the spectral dependence of α from the spectral foam reflectance R is proposed. *INDEX TERMS:* 4552 Oceanography: Physical: Ocean optics; 4594 Oceanography: Physical: Instruments and techniques; 0694 Electromagnetics: Instrumentation and techniques; 4546 Oceanography: Physical: Nearshore processes; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; *KEYWORDS:* foam, light scattering, ocean optics

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1. Introduction

[2] Whitecaps cover a great surface area S of all the world's oceans. In particular, *Monahan* [2001] estimates that S = 70,000 km^2 for stage A whitecaps. It can be deduced that some 720,000 km^2 of individual bubble surface area are destroyed each second in all the stage A whitecaps present on the surface of all the oceans. An equal bubble surface area is being generated in the same interval. This has profound implications for the global rate of air-ocean exchange of moisture, heat, and gases. Also, because of the highly reflecting properties of whitecaps at the maximum of the solar spectral flux, they insert a cooling influence on the planet by increasing surface albedo [*Frouin et al.*, 2001]. Whitecaps also influence aerosol and oceanic color remote sensing from space [*Koepke and Quenzel*, 1981; *Whitlock et al.*, 1982; *Gordon*, 1997].

[3] All these processes being of a global nature require global means of observation. In particular, the estimations of S, the geometrical thicknesses of whitecaps H, the sizes of air bubbles d, and the void fractions f from spaceborne instrumentations are of paramount importance. The value of H alters the emissivity of whitecaps [*Reul and Chapron*, 2003]. This can be detected by an orbiting microwave radiometer [*Cherny and Raizer*, 1998]. Optical instruments of a high spatial resolution can be used to estimate S. Sizes of bubbles, void fractions, and spectral absorption coefficient of liquid in films can be estimated from whitecap spectral signatures in the near infrared. The realization of this ambitious program requires detailed experimental and theoretical studies of the interaction of electromagnetic waves with foamed media.

[4] Experimental studies of spectral and radiative properties of whitecaps have attracted considerable attention in recent years. In particular, spectral reflectance of whitecaps was measured in a broad spectral range from the visible to the infrared [*Frouin et al.*, 1996; *Moore et al.*, 1998, 2000; *Nicolas et al.*, 2001]. Theory did not follow the progress in experimental studies of optical properties of whitecaps. This is mostly due to the fact that foam is a very unusual medium from the point of view of the radiative transfer theory [*Chandrasekhar*, 1950], which is a standard tool for studies of light propagation in natural media with low concentration of scatterers. Indeed, the volumetric concentration of bubbles in whitecaps is larger than 70% in most cases. The radiative transfer equation, however, is usually applied to the case of media with a low concentration of scatterers (smaller than 1% by volume). Therefore one should use the so-called dense media theory (DMT) [*Tsang et al.*, 2001], which requires large computational resources and is not very suitable for satellite operational algorithms. The DMT

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is of great importance for the microwave region, where sizes of bubbles are of the order of the wavelength [*Guo et al.*, 2001]. In the visible range, because of the large sizes d of scatterers as compared with the wavelength λ, the geometrical optics approximation is valid, which simplifies calculations to a great extent and can generate a range of useful approximations [see, e.g., *Stabeno and Monahan*, 1986]. It is believed that Monte Carlo techniques [*Chen et al.*, 2003] coupled with the geometrical optics approximation have great potential in the optics of whitecaps.

[5] The aim of this paper is the development of the phenomenological optics of whitecaps. In particular, we propose simple approximate equations for the calculation of the spectral reflectance of whitecaps and show its consistency with available measurements. Our theory can be considered as a further step in the construction of the optics of whitecaps, which is currently under development.

[6] The structure of the paper is as follows. In section 2 we propose a simple analytical equation to calculate the foam spectral albedo and its reflection function. Section 3 is devoted to the comparison of derived results with available experimental data.

2. Theory

[7] The spherical albedo r [*van de Hulst*, 1980] is defined as the integral of the azimuthally averaged reflection function with respect to the incidence and observation angles. By definition, it is equal to 1 for nonabsorbing semi-infinite light-scattering media.

[8] We seek a simple analytical equation for the spherical albedo of whitecaps, which can be used, for example, in oceanic sections of global circulation models and also in satellite aerosol and ocean remote sensing. We assume that whitecaps can be presented as semi-infinite media. However, this assumption is not crucial. Indeed, the theory of light reflection by a semi-infinite medium can be easily extended (after simple transformations) to the case of finite but optically thick media.

[9] We start from a quite general representation of the spherical albedo as the Maclauren series with respect to the single scattering albedo ω_0,

$$r = \sum_{n=1}^{\infty} a_n \omega_0^n, \tag{1}$$

for nonabsorbing media $r = \omega_0 = 1$, and therefore

$$\sum_{n=1}^{\infty} a_n = 1. \tag{2}$$

Equation (1) is an exact result. The coefficients a_n give contributions of n scattering into the value of albedo r. Whitecaps are weakly absorbing, highly light-scattering media. This means that we should account for a large number of terms in equation (1). To avoid this, we introduce the probability of photon absorption $\beta = 1 - \omega_0$, which is a small number for whitecaps. Then it follows from equation (1) that

$$r = \sum_{n=1}^{\infty} a_n (1 - \omega_0)^n. \tag{3}$$

This can be rewritten as

$$r = 1 - \langle n \rangle \beta + 0.5 \langle n(n-1) \rangle \beta^2 - \ldots, \tag{4}$$

where $\langle n \rangle = \sum_{n=1}^{\infty} n a_n$ and likewise for other terms. Whitecaps belong to a broad class of strongly multiple-scattering media. This means that $\langle n \rangle$ is a large number, and therefore $\langle n(n-1) \rangle \approx \langle n^2 \rangle$ and likewise for higher-order terms. Thus we have approximately

$$r = 1 - \langle n \rangle \beta + 0.5 \langle n^2 \rangle \beta^2 - \ldots \approx \exp(-N\beta). \tag{5}$$

The constant N is generally unknown. We find N using the fact that [*van de Hulst*, 1980]

$$r = 1 - 4\sqrt{\frac{\beta}{3(1-g)}} \tag{6}$$

for small β. Here g is the asymmetry parameter, which describes the elongation of the phase function of whitecaps in the forward direction [*van de Hulst*, 1980]. Therefore we finally have

$$r = \exp\left[-4\sqrt{\frac{\beta}{3(1-g)}}\right]. \tag{7}$$

We will use this formula for the interpretation of laboratory and in situ measurements of the spectral reflectance of whitecaps in section 3.

[10] The accuracy of equation (7) is shown in Figure 1 as compared with the full solution of the integrodifferential radiative transfer equation for a semi-infinite layer given by *Yanovitskij* [1997] in tabular form. We see that the approximation is very accurate at $r > 0.4$. The error is below 7% at $r > 0.25$, which can be considered as a theoretical limit for the use of this approximation. The value of r is close to one in the visible range for whitecaps. Thus there should be no problems with the application of this formula in the case studied. Equation (7) is similar to that derived by *Rozenberg* [1962]. It has been used successfully in various light-scattering media optics studies [see, e.g., *Zege et al.*, 1991a, 1991b; *Kokhanovsky and Zege*, 2004].

[11] Let us rewrite equation (7) in a more convenient form using notions of the absorption path length l_{abs},

$$l_{\mathrm{abs}} = \frac{l}{\beta}, \tag{8}$$

and the transport photon path length l_{tr},

$$l_{\mathrm{tr}} = \frac{l}{1-g}. \tag{9}$$

Here l is the average distance between scattering events, which is given by the inverse value of the total scattering coefficient of the medium. We assume that extinction and scattering path lengths are almost equal in whitecaps

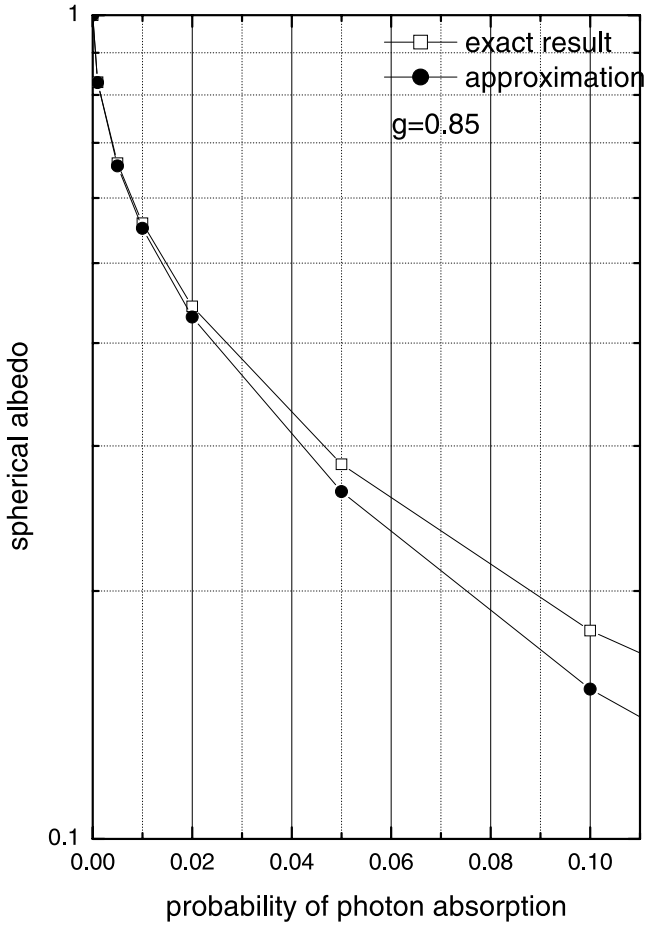

Figure 1. Comparison of results obtained from equation (7) with exact calculations.

because of small light absorption by thin water films in visible and near-infrared regions of the electromagnetic spectrum. This assumption does not hold for regions free of whitecaps. There our theory is not valid, and one should use the numerical solution of the radiative transfer equation or other approximate techniques.

[12] The next step is to relate l_{abs} and l_{tr} with microphysical characteristics of whitecaps such as the liquid fraction c and the average diameter of bubbles d. For this we will use an empirically established relation [*Vera et al.*, 2001]

$$l_{tr} = \frac{d}{\sqrt{c}}. \tag{10}$$

Also, we will assume that l_{abs} is inversely proportional to the product of the liquid bulk absorption coefficient α and the liquid concentration c. Then it follows that

$$l_{abs} = \frac{D}{\alpha c}, \tag{11}$$

where D is a generally unknown constant. Our previous studies [*Kokhanovsky and Zege*, 2004] show that the dependence of this constant on α and c is weak. D depends mostly on the real part of the relative refractive index $Re(m)$ of liquid in whitecaps. We find that D is close to 1 for media with $Re(m) \approx 1$. Thus D should be also rather close to 1 for whitecaps. It follows from equation (7), taking into account considerations given above, that

$$r = \exp\left(-Bc^{1/4}\sqrt{\alpha d}\right), \tag{12}$$

where $B = 4/\sqrt{3D}$. This is the main result of this work. The constant B should be found from experimental measurements (e.g., using equation (12) itself). In particular, we have $B \approx 2.3$ in the assumption $D = 1$.

[13] Equation (12) can be rewritten in a different form for dry foams having values of d inversely proportional to c. Since

$$d = M\frac{\delta}{c} \tag{13}$$

[*Kruglyakov and Ekserova*, 1990], where δ is the average film thickness and M varies in the range 1.35–1.64 depending on the form of a foam cell, equation (12) is written as

$$r = \exp\left(-G\sqrt{cp}\right), \tag{14}$$

where $p = \alpha\delta$ and $G = B\sqrt{M}$ ($\approx$3.5 at $D = 1$, $M = 1.5$). Obviously, $E = \exp(-p)$ gives the light attenuation on its passage through a single film.

[14] We would like to emphasize that equation (12) can be used to find the plane albedo r_p and the reflection function R of whitecaps using the following results valid for weakly absorbing, strongly light-scattering media [*Zege et al.*, 1991a]:

$$r_p = r^q, \; R = R_0 r^Q, \tag{15}$$

where [*Zege et al.*, 1991b]

$$q = \frac{3(1+2\cos\theta_0)}{7}, \; Q = \frac{q(\theta)q(\theta_0)}{R_0}. \tag{16}$$

Here R_0 is the reflection function at $\omega_0 = 1$ and θ_0 and θ are incidence and observation angles, respectively. The equations given above are easily generalized for the case of finite optically thick layers having the geometrical thickness L. Then we have [*Kokhanovsky et al.*, 2003]

$$R_L = R - (r - r_L)q(\theta)q(\theta_0), \tag{17}$$

where R_L and r_L are reflection functions and spherical albedos of finite optically thick layers, respectively. In particular, it follows that [*Kokhanovsky et al.*, 2003]

$$r_L = \frac{\sinh(hy)}{\sinh(hy+y)}, \tag{18}$$

where $y = 4\sqrt{l_{tr}/3l_{abs}}$ and $h = 3L/4l_{tr}$. Moreover, we have for the transmission function

$$T = t_L q(\theta)q(\theta_0), \tag{19}$$

where

$$t_L = \frac{\sinh(y)}{\sinh(hy + y)} \tag{20}$$

is the diffused transmission under diffused illumination conditions. Note that $t_L = (1 + h)^{-1}$ and $r_L = h(1 + h)^{-1}$ at $\omega_0 = 1$. Because of the uncertainty introduced by the various assumptions involved, our theory should be carefully checked against experimental results obtained to date. Also, new (preferably, laboratory) experiments should be performed to check the prediction of our theory (e.g., for the same foam, but with different spectra $\alpha(\lambda)$). Some of these experiments are discussed in light of our theory in section 3.

3. Interpretation of Experimental Data

3.1. Laboratory Experiment

[15] Laboratory measurements of the foam spectral reflectance were performed by *Whitlock et al.* [1982] using tap water and detergents. Although sizes of bubbles and their concentrations and dependencies $\alpha(\lambda)$ in the experiment of *Whitlock et al.* [1982] do not coincide with typical values in the open ocean, these measurements still can be used to check our theory.

[16] In particular, *Whitlock et al.* [1982] found that the measured foam spectral reflectance can be approximated by the following polynomial at wavelengths larger than 0.8 μm (see Figure 2):

$$R = \sum_{j=0}^{4} (-1)^j \xi_j (ln\alpha_w)^j, \tag{21}$$

where $\xi_0 = 60.063$, $\xi_1 = 5.127$, $\xi_2 = 2.799$, $\xi_3 = 0.713$, and $\xi_4 = 0.044$. Note that the bulk water absorption coefficient $\alpha_w = (4\pi k)/\lambda$ is expressed in m^{-1}. Here k is the imaginary part of the refractive index of water.

[17] Equation (21) has the correlation coefficient 0.979 and the standard error equal to 4.36 at wavelengths larger than 0.8 μm, as compared with actual measurements. For smaller wavelengths it was found that foam is almost spectrally neutral. *Whitlock et al.* [1982] stressed that the polynomial regression equations usually give few clues to actual physical relationships of the parameters being correlated.

[18] Let us compare now the physically based parameterization (12) with experimental data. For this we rewrite equation (12) in the following form:

$$r = \exp\left(-\sqrt{\alpha s}\right), \tag{22}$$

where

$$s = B^2 d\sqrt{c}. \tag{23}$$

Whitlock et al. [1982] measured not the value of r itself but rather the spectral reflection function R at a given geometry of illumination and observation. It follows for R that

$$R = R_0 \exp\left(-\sqrt{\alpha b}\right), \tag{24}$$

where $b = sQ^2$.

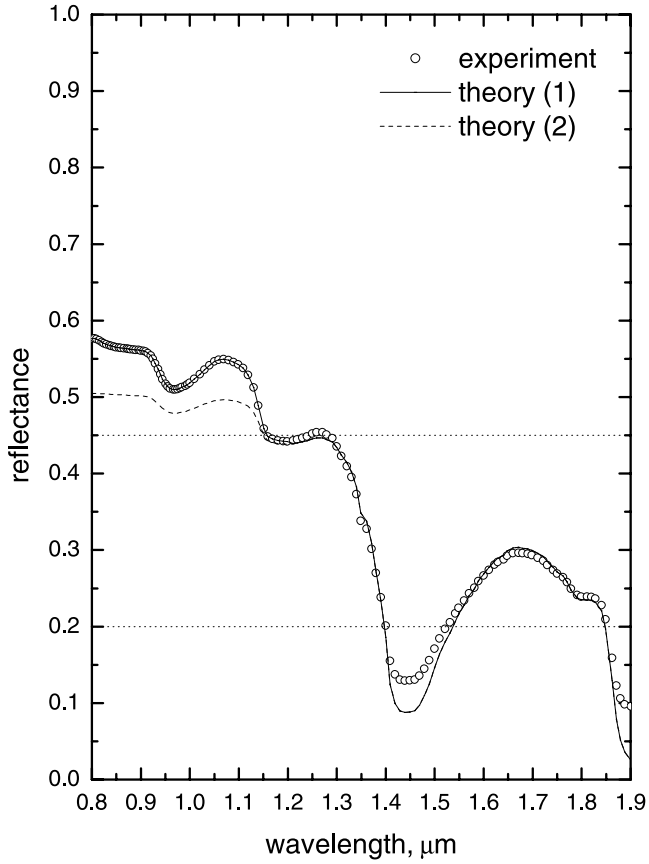

Figure 2. Foam spectral reflectance calculated using equation (21) (experiment of *Whitlock et al.* [1982]) and equation (24) (theory). Theoretical results differ because of a different choice of the absorption coefficient of additives, which was not specified in the experiment. The value of b in equation (24) was taken to be equal to 1.72 mm.

[19] We account for the fact that the absorption coefficient in the experiment was close to that of water for large wavelengths λ. This is due to an appreciable absorption by water at wavelengths larger than approximately 1.2 μm. For shorter wavelengths, light absorption by dissolved substances can play a role. Therefore we used $\alpha = \alpha_w + c^*\alpha_a$, where α_w is the absorption coefficient of pure water and α_a is the absorption coefficient of additives (e.g., detergents), which were present in the water during the experiment. The value of c^* gives the relative volumetric concentration of additives.

[20] Equation (24) fits experimental measurements pretty well (see Figure 2), which confirms the applicability of our derivations and assumptions. The dashed line in Figure 2 corresponds to calculations using equation (24) at $R_0 = 1$ and the spectrally neutral value of $c^*\alpha_a$, which

was set equal to 0.00027 μm^{-1}. The value of α_w was taken from *Segelstein* [1981]. We see that the assumption of an additional spectrally neutral absorber does not work for wavelengths smaller than 1.2 μm. *Whitlock et al.* [1982] did not specify the value of $c^*\alpha_a$ for their experiment, so we obtained the function $c^*\alpha_a(\lambda)$ at λ smaller than 1.2 μm from the experimental data themselves, using equation (24). The results are shown in Figure 2 by a solid line. Solid and dashed lines coincide at $\lambda \geq 1.2$ μm.

[21] Overall, equation (24) can be used for the interpretation of the experimental reflectance given in Figure 2 in the range of $R = 0.2-0.45$ (without taking into account any spectrally varying additional absorbers). For larger values of R a spectral variation of additives should be taken into account. Equation (24) has larger errors for smaller values of R (see Figure 2) due to the violation of a weak absorption assumption in this case, and here equation (24) is not valid.

[22] The value of b in equation (24) was taken to be equal to 1.72 mm, a value found by a fitting procedure. It is of importance to estimate values of R_0 and b not by applying the fitting procedure but from the physics of the problem. Unfortunately, *Whitlock et al.* [1982] did not give full details of the experiment, so we can only make a rough estimate of these parameters, which are possibly biased because of the unknown density and microstructure of foam used in the experiment.

[23] The value of R_0 coincides with the reflection function of a semi-infinite nonabsorbing medium. We can conclude from Figure 1 of *Whitlock et al.* [1982] that the measurements are performed at near-nadir observation and illumination conditions. Then R_0 and therefore R_0 should be close to 1 [*Kokhanovsky*, 2001] as in Figure 2. The value of b is given by the product $B^2\sqrt{c}Q^2d$. We obtain the following estimates for multipliers: $Q \approx 1.65$ (for nadir illumination and observation conditions, see equation (16)) and $B \approx 2.3$. Taking into account that $b \approx 1.72$ mm for Figure 2, we obtain $d\sqrt{c} = 0.12$ mm, which is a reasonable estimate (e.g., $d = 1.2$ mm and $c = 0.01$).

[24] We stress that experimental data and theory coinciding in Figure 2 is not a final proof of our theory because of all uncertainties involved. However, it does prove the concept. In particular, the foam spectral reflectance is governed by the dependence $\exp[-\sqrt{b\alpha(\lambda)}]$, where $\alpha(\lambda)$ is the spectral reflectance of liquid in foam and b is the spectrally neutral constant. This is a major conclusion of this work. Note that our approach allows reduction of the number of unknown coefficients in the description of the spectral reflectance in experimental data given in Figure 2 from five as in equation (21) to just one. Also, the approach is capable of describing other experimental data (see section 3.2), which is not the case for equation (21).

3.2. Experiments in the Surf Zone and Open Ocean

[25] Let us consider now the results of measurements of sea foam spectral reflectance performed at the Scripps Institution Oceanography Pier, La Jolla, California. *Frouin et al.* [1996] measured the spectral reflectance of sea foam by viewing the sea surface radiometrically in a region of breaking waves near the pier. They found that the foam reflectance decreases substantially with wavelength in the near infrared, contrary to the findings of previous studies, theoretical as well as experimental. In particular, it follows from Figure 2 that the foam reflectance does not change considerably at wavelengths smaller than 1.2 μm [*Whitlock et al.*, 1982]. This was not confirmed by *Frouin et al.* [1996] for measurements in situ.

[26] This discrepancy can be understood using our simple model. It follows from equation (12) that the spectral reflectance of whitecaps depends strongly on the spectral absorption coefficient α of water. We stress that values of natural water absorption coefficient can vary considerably because of the presence of dissolved and particulate matter [*Bricaud et al.*, 1998]. This causes the variation of the foam spectral reflectance across the ocean. The filtered-deionized tap water used by *Whitlock et al.* [1982] differs considerably from the surf water in the experiment of *Frouin et al.* [1996] (e.g., in terms of their spectral absorption coefficient), and the void fractions and bubble spectra are also different. These are the main reasons behind differences obtained in these two experiments.

[27] Our theory can be applied to the experiment of *Frouin et al.* [1996]. For this we need to know the value of the water absorption coefficient. This, unfortunately, was not measured during the experiment. Therefore we use the parameterization of the oceanic water absorption coefficient, proposed by *Morel and Maritorena* [2001] (see Appendix A) to describe the experiment of Frouin et al.

[28] The comparison of experimental data and the theory for the normalized foam reflectance $R_n(\lambda) = R(\lambda)/R(0.44\ \mu m)$ at the visible band of the electromagnetic spectrum is shown in Figure 3. We see that equation (24) (used in combination with data for α given in Appendix A) makes it possible to explain the foam spectral selectivity in the visible. The value of $b = 17.1$ mm used in Figure 3 was found by the fitting procedure. This is approximately 10 times larger than in the experiment of *Whitlock et al.* [1982] and can be attributed to larger values of the constant b in the experiment compared with measurements performed by Whitlock et al. This can be explained, for example, by larger values of the void fraction in the laboratory foam as compared with the measurements near the pier.

[29] We compared *Frouin et al.*'s [1996] measurements with results of our theoretical model in the infrared (see Figure 4), using the same value of b as in Figure 3. The pure water absorption coefficient was taken from data of *Segelstein* [1981]. The influence of additional absorbers like yellow substance and pigments was neglected at wavelengths larger than 0.7 μm. The experiment of Frouin et al. showed that the foam spectral reflectance reduced by typically 40% at the wavelength 0.85 μm, 50% at 1.02 μm, and 85% at 1.65 μm. A 50% reduction is found at 1.02 μm (see Figure 3). However, the theory gives only 25% reduction at 0.85 μm. It is 95% at 1.65 μm. The last number could be biased because our approximation has poor accuracy in the region of large absorption (see Figure 1). The discrepancy at 0.85 μm

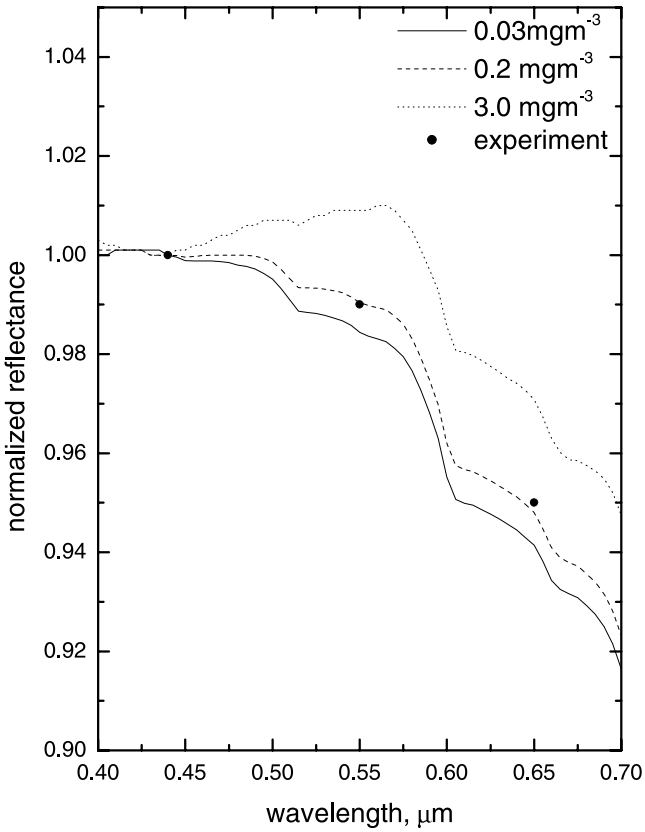

Figure 3. Normalized spectral reflectance of foam in the surf zone calculated using equation (24) at b = 17.1 mm with α specified in Appendix A for different chlorophyll contents. Experimental data are taken from *Frouin et al.* [1996].

could be due to various reasons. One of them is the possible presence of an additional absorber during the experiment, which is always the case near a pier. This is supported by data obtained by *Moore et al.* [2000], who found that the value of the normalized reflectance is only 0.8 at the wavelength 0.86 μm in open ocean for wind speeds 9–12 m s^{-1}. This closely corresponds to theoretical results given in Figure 4 at this wavelength. *Moore et al.* [2000] suggest, however, another reason for the discrepancy, namely, the less violent wave breaking in the open ocean as compared with the surf zone. This leads to the decrease of d and therefore b, which in turn enhances R. Bubbles in the surf zone are much more likely to be stabilized by natural surfactants in an immediate coastal region [*Bortkovskii*, 1987] than are bubbles in whitecaps on the open ocean, which could also add to the discrepancy.

[30] *Nicolas et al.* [2001] found that the normalized reflectance at 0.855 μm is close to 0.65 with the standard deviation 0.15 for 15 cases measured in open ocean. At first sight this contradicts the data of *Moore et al.* [2000]. However, *Nicolas et al.* [2001] have used the push-boom radiometer with the spectral bandwidth 0.19 μm (see Figure 4) at the central wavelength 0.855 μm. *Moore et al.* [2000] used a six-channel radiometer with the nominal 0.01 μm spectral width. Because of a high variation of the normalized reflectance (0.4–0.8) in the range 0.76–0.95 μm (see Figure 4) the result should be highly sensitive to the radiometer spectral response function and the bandwidth in this particular case. This may explain the differences obtained.

[31] The so-called spectral factor is shown in Figure 4. This factor was introduced by *Frouin et al.* [2001] in such a way that the product $R_{ef}f(\lambda)$ gives the spectral albedo of whitecaps. Here R_{ef} is the so-called whitecap effective albedo. In particular, *Koepke* [1984] gives R_{ef} = 0.22 with the standard deviation 0.11. *Frouin et al.* [2001] used the following parameterization for the spectral factor at wavelength larger than 0.6 μm: $f = \exp[-V(\lambda - 0.6)^W]$, where V = 1.75 with the standard deviation 0.48 and W = 0.99 with the standard deviation 0.05. It was assumed that f = 1 for smaller wavelengths. We show this parameterization by a dashed line in Figure 3. We believe that equation (24) allows for a more correct description of the spectral factor. Namely, we have $f = \exp(-\sqrt{\alpha b})$, which accounts for the water

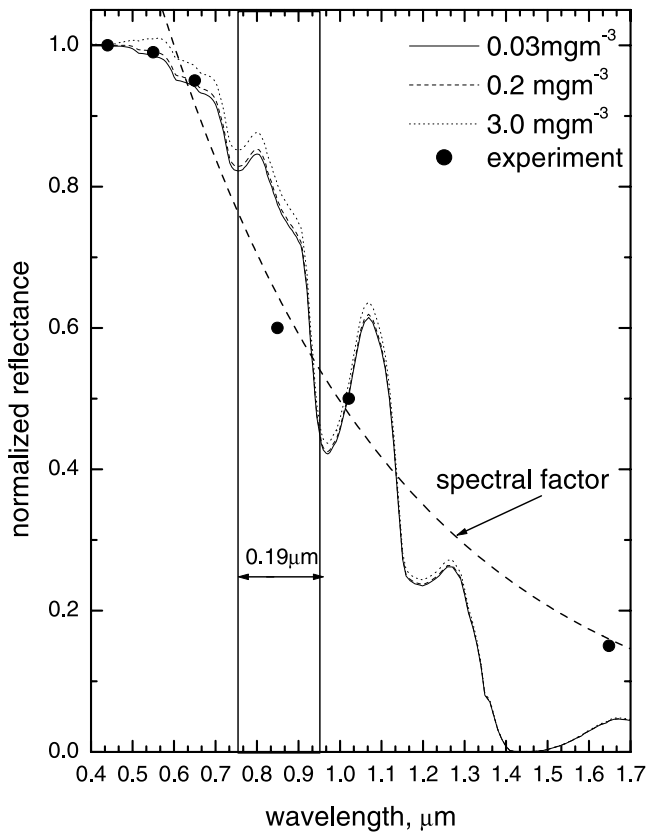

Figure 4. Same as in Figure 2 but for the broader spectral range. The spectral factor f [*Frouin et al.*, 2001] is also shown. Vertical lines show the bandwidth (0.19 μm) of channel 3 of the radiometer used by *Nicolas et al.* [2001] for measurements performed in open ocean.

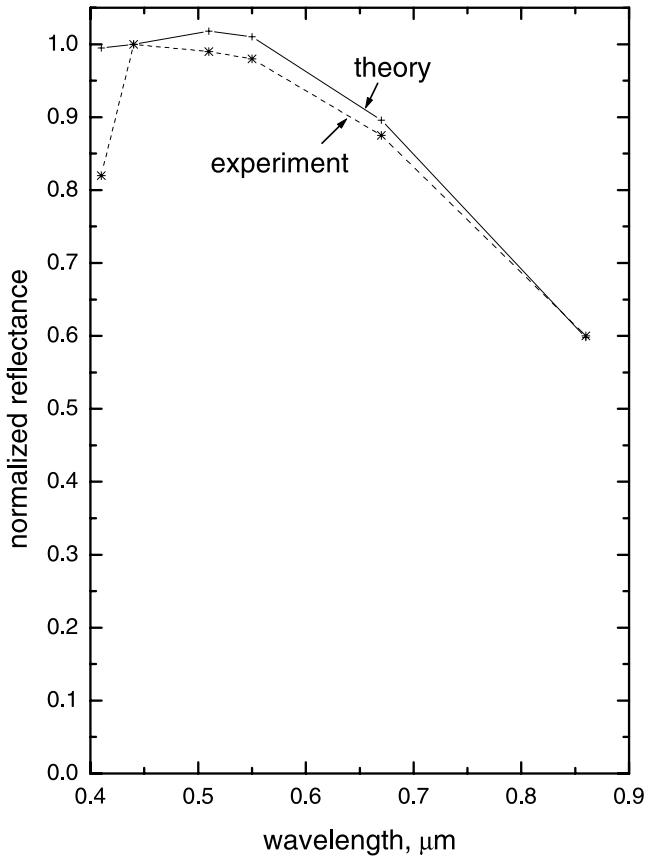

Figure 5. Normalized spectral reflectance of whitecaps calculated from equation (24), using values of α given by *Moore et al.* [1998] and $b = 85.5$ mm (theory). Experimental data are taken from Figure 10 of *Moore et al.* [1998].

spectral absorption. The constant b depends on the type of foam and should be found experimentally.

[32] For the sake of completeness we would like to mention the experiment of *Moore et al.* [1998], which was carried out on ship-induced foam. The normalized reflectance obtained from this experiment and equation (24) using the values of α reported by *Moore et al.* [1998] (0.11, 0.1, 0.065, 0.08, 0.475, and 4.3 m^{-1} at wavelengths 0.41, 0.44, 0.51, 0.55, 0.67, and 0.865 μm, respectively) are shown in Figure 5. The value of b was taken equal to 85.5 mm to fit the experimental data. Equation (24) can be used as an accurate basis for the fitting procedure, which explains the foam spectral dependence. However, the experimental data do not show the correlation with the water absorption coefficient provided by Moore et al. at the wavelengths 0.41 and 0.44 μm. The absorption coefficient given by Moore et al. decreases in the range 0.44–0.55 μm, while the experimental spectral reflectance also decreases in this range. This is in contradiction to the theory presented in section 2 and to physical dependencies, which are expected in this case. Most probably, values of α given by Moore et al. correspond to pure oceanic water, which differs from water close to the ship because of various sources of contamination. This may also explain a great reduction of the normalized foam reflectance at the wavelength 0.86 μm obtained in this case (see Figure 5).

4. Conclusion

[33] A simple analytical parameterization (equation (24)) of the foam spectral reflectance is proposed. The values of b in equation (24) were found to be approximately equal to 2, 17, and 85 mm, depending on the experiment and therefore on foam structure. Equation (24) can be used, for example, to account for whitecaps in a number of remote sensing applications. For this, however, the whitecap coverage area A in the pixel should be known or estimated. Then the reflection function associated with a given pixel is a linear mixture of the clear water contribution and the foam-covered area reflectance weighted taking into account A. We also indirectly show that the radiative transfer equation can be applied to studies of light propagation in foams. However, there is no simple way to calculate local optical characteristics of foams. Therefore experimental techniques should be used to provide information on phenomenological constants R_0 and b, depending on the foam microstructure (dry or wet foam, etc.).

[34] We also stress that the results obtained can be used for the development of the foamed media spectroscopy. In particular, the relative surface water absorption coefficient can be easily obtained from measurements of the reflection function R (see equation (24)).

[35] Both theory and experiment point to a marked spectral dependence of foam reflectance, which strongly correlates with the surface water absorption coefficient. The failure to account for this effect can lead to biases in modern ocean color remote sensing algorithms.

[36] Also, spectral signatures of whitecaps (see, e.g., equation (24)) should be included in the next generation of coupled climate models. This will allow for a better assessment of the impact of whitecaps on the planetary albedo and climate.

Appendix A: Oceanic Water Absorption Coefficient

[37] For the sake of completeness we present here a model for the oceanic water absorption coefficient α, given by *Morel and Maritorena* [2001]. We also present experimental data of *Prieur and Sathyendranath* [1981] for the spectral pigment absorption coefficient $p(\lambda)$ normalized at the wavelength 440 nm and data of *Pope and Fry* [1997] for the pure water absorption coefficient α_w in tabular form (see Table A1). This is included to make it possible to model $\alpha(\lambda)$ (and therefore $R(\lambda)$) without having to resort to other sources.

[38] *Morel and Maritorena* [2001] have introduced the following parameterization for α: $\alpha = C_p\alpha_p + C_y\alpha_y + \alpha_w$, where $C_p\alpha_p$ gives the product of pigment concentration and its absorption coefficient and $C_y\alpha_y$ is the product of the concentration of yellow substance and its absorption coefficient. We used the following parameterizations [*Morel and Maritorena*, 2001]: $C_p\alpha_p = 0.2[\alpha_w(\lambda_0) + 0.06x^{0.65}] \exp[-0.014(\lambda - \lambda_0)]$ and $C_y\alpha_y = 0.06p(\lambda)$, where λ is given in nm, $\lambda_0 = 440$ nm, and x is the chlorophyll

Table A1. Functions $\alpha_w(\lambda)$[a] and $p(\lambda)$[b]

λ, nm	α_w, m^{-1}	p
0.4000E+03	0.6630E-02	0.6870E+00
0.4050E+03	0.5300E-02	0.7810E+00
0.4100E+03	0.4730E-02	0.8280E+00
0.4150E+03	0.4440E-02	0.8830E+00
0.4200E+03	0.4540E-02	0.9130E+00
0.4250E+03	0.4780E-02	0.9390E+00
0.4300E+03	0.4950E-02	0.9730E+00
0.4350E+03	0.5300E-02	0.1001E+01
0.4400E+03	0.6350E-02	0.1000E+01
0.4450E+03	0.7510E-02	0.9710E+00
0.4500E+03	0.9220E-02	0.9440E+00
0.4550E+03	0.9620E-02	0.9280E+00
0.4600E+03	0.9790E-02	0.9170E+00
0.4650E+03	0.1011E-01	0.9020E+00
0.4700E+03	0.1060E-01	0.8700E+00
0.4750E+03	0.1140E-01	0.8390E+00
0.4800E+03	0.1270E-01	0.7980E+00
0.4850E+03	0.1360E-01	0.7730E+00
0.4900E+03	0.1500E-01	0.7500E+00
0.4950E+03	0.1730E-01	0.7170E+00
0.5000E+03	0.2040E-01	0.6680E+00
0.5050E+03	0.2560E-01	0.6450E+00
0.5100E+03	0.3250E-01	0.6180E+00
0.5150E+03	0.3960E-01	0.5820E+00
0.5200E+03	0.4090E-01	0.5280E+00
0.5250E+03	0.4170E-01	0.5040E+00
0.5300E+03	0.4340E-01	0.4740E+00
0.5350E+03	0.4520E-01	0.4440E+00
0.5400E+03	0.4740E-01	0.4160E+00
0.5450E+03	0.5110E-01	0.3840E+00
0.5500E+03	0.5650E-01	0.3570E+00
0.5550E+03	0.5960E-01	0.3210E+00
0.5600E+03	0.6190E-01	0.2940E+00
0.5650E+03	0.6420E-01	0.2730E+00
0.5700E+03	0.6950E-01	0.2760E+00
0.5750E+03	0.7720E-01	0.2680E+00
0.5800E+03	0.8960E-01	0.2910E+00
0.5850E+03	0.1100E+00	0.2740E+00
0.5900E+03	0.1351E+00	0.2820E+00
0.5950E+03	0.1672E+00	0.2490E+00
0.6000E+03	0.2224E+00	0.2360E+00
0.6050E+03	0.2577E+00	0.2790E+00
0.6100E+03	0.2644E+00	0.2520E+00
0.6150E+03	0.2678E+00	0.2680E+00
0.6200E+03	0.2755E+00	0.2760E+00
0.6250E+03	0.2834E+00	0.2990E+00
0.6300E+03	0.2916E+00	0.3170E+00
0.6350E+03	0.3012E+00	0.3330E+00
0.6400E+03	0.3108E+00	0.3340E+00
0.6450E+03	0.3250E+00	0.3260E+00
0.6500E+03	0.3400E+00	0.3560E+00
0.6550E+03	0.3710E+00	0.3890E+00
0.6600E+03	0.4100E+00	0.4410E+00
0.6650E+03	0.4290E+00	0.5340E+00
0.6700E+03	0.4390E+00	0.5950E+00
0.6750E+03	0.4480E+00	0.5440E+00
0.6800E+03	0.4650E+00	0.5020E+00
0.6850E+03	0.4860E+00	0.4200E+00
0.6900E+03	0.5160E+00	0.3290E+00
0.6950E+03	0.5590E+00	0.2620E+00
0.7000E+03	0.6240E+00	0.2150E+00

[a] *Pope and Fry* [1997].
[b] *Prieur and Sathyendranath* [1981].

concentration (in mg m^{-3}). Note that x is usually in the range 0.03–3 mg m^{-3}.

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